Characterization of a Fully Depleted CCD on High Resistivity Silicon

R. J. Stover[a], M. Wei[a], Y. Lee[a], D. K. Gilmore[a]
S. E. Holland[b], D. E. Groom[b], W. W. Moses[b]
S. Perlmutter[b] G. Goldhaber[b], C. Pennypacker[b], N. W. Wang[b], and N. Palaio[b]

[a]University of California Observatories/Lick Observatory, University of California Santa Cruz
[b]Lawrence Berkeley National Laboratory, University of California, Berkeley

ABSTRACT

Most scientific CCD imagers are fabricated on 30-50 Ω-cm epitaxial silicon. When illuminated from the front side of the device they generally have low quantum efficiency in the blue region of the visible spectrum because of strong absorption in the polycrystalline silicon gates as well as poor quantum efficiency in the far red and near infrared region of the spectrum because of the shallow depletion depth of the low-resistivity silicon. To enhance the blue response of scientific CCDs they are often thinned and illuminated from the back side. While blue response is greatly enhanced by this process, it is expensive and it introduces additional problems for the red end of the spectrum. A typical thinned CCD is 15 to 25 µm thick, and at wavelengths beyond about 800 nm the absorption depth becomes comparable to the thickness of the device, leading to interference fringes from reflected light. Because these interference fringes are of high order, the spatial pattern of the fringes is extremely sensitive to small changes in the optical illumination of the detector. Calibration and removal of the effects of the fringes is one of the primary limitations on the performance of astronomical images taken at wavelengths of 800 nm or more.

In this paper we present results from the characterization of a CCD which promises to address many of the problems of typical thinned CCDs. The CCD reported on here was fabricated at Lawrence Berkeley National Laboratory on a 10-12 KΩ-cm n-type silicon substrate. The CCD is a 200X200 15-µm square pixel array, and due to the very high resistivity of the starting material, the entire 300 µm substrate is depleted. Full depletion works because of the gettering technology developed at Lawrence Berkeley National Laboratory which keeps leakage current down. Both front-side illuminated and backside illuminated devices have been tested. We have measured quantum efficiency, read-noise, full-well, charge-transfer efficiency, and leakage current. We have also observed the effects of clocking waveform shapes on spurious charge generation.

While these new CCDs promise to be a major advance in CCD technology, they too have limitations such as charge spreading and cosmic-ray effects. These limitations have been characterized and are presented. Examples of astronomical observations obtained with the backside CCD on the 1-meter reflector at Lick Observatory are presented.

Keywords: CCD, high resistivity, fully depleted, Lick Observatory, Lawrence Berkeley National Laboratory, astronomical

2. DESIGN AND FABRICATION

A detailed discussion of the design and fabrication of these devices is given elsewhere[1]. These devices are based on work done at Lawrence Berkeley National Laboratory to develop fully-depleted p-i-n diodes for high-energy physics applications, and all design and fabrication work on the CCDs was carried out there. The starting material for these devices is approximately 10,000 Ω-cm float-zone refined n-type silicon, in 300 µm thick wafers. After computer modeling of various amplifier and pixel structures, a final design was chosen which employs 15 µm square pixels in a 200x200 array. Standard triple-poly MOS processing was used in fabrication. One of the key elements in the success of these devices is the deposition of a phosphorous doped polysilicon layer on the back surface of the wafer for gettering purposes[2].

3. LABORATORY CHARACTERIZATIONS

3.1 Device selection and preparation

After fabrication, devices were tested on the wafer using a probe station in the Detector Development Laboratory of the University of California Observatories/Lick Observatory (UCO/Lick) in Santa Cruz. The best devices were identified and selected for further processing and packaging. The CCDs were mounted on an aluminum nitride substrate which was patterned to provide the backside bias contact and pads for wire-bonding to the device pads. The aluminum nitride provides a good thermal expansion match to silicon and is a good thermal conductor. The CCD was attached to the aluminum nitride with conductive epoxy to achieve electrical contact with the backside bias connection, a 50 nm thick layer of indium tin oxide (ITO). For the backside-illuminated devices the aluminum nitride substrate was removed in the area of the CCD and the substrate was inverted and mounted in a specially prepared commercial kovar package. Figure 1 (not to scale) illustrates the mounting scheme. The mounting for this backside-illuminated device is much simpler than for a standard thinned CCD because the device is still 300 μm thick and is self-supporting.

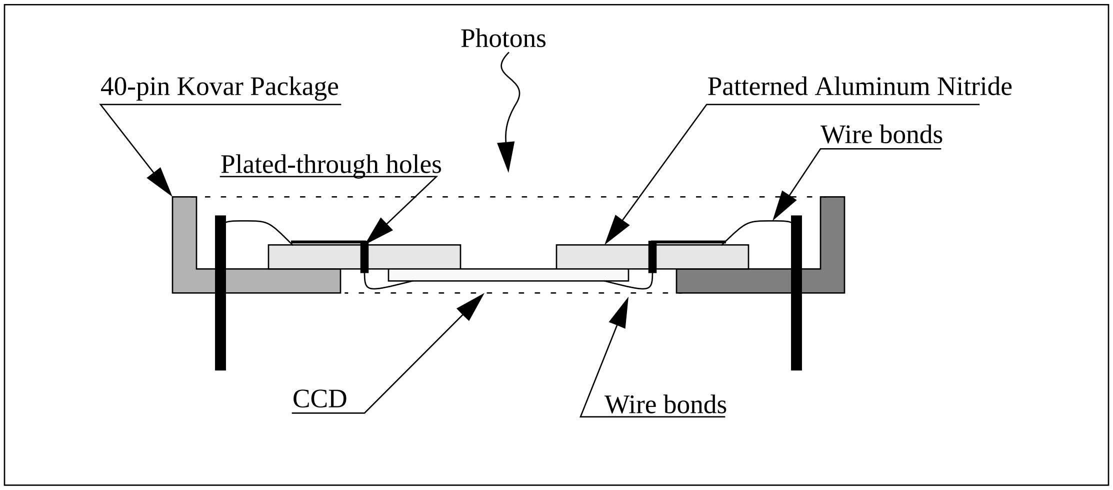

FIGURE 1. A schematic drawing of the simple mounting for a backside-illuminated CCD.

3.2 Device characterization

Packaged devices were tested in the UCO/Lick Detector Development Laboratory using the standard Lick CCD data acquisition system[3]. The CCD controller uses a double-correlated amplifier with 16 μsec integration times on both baseline and data, and a 16-bit analog-to-digital converter. Operating parameters are summarized in Table 1.

TABLE 1. Operating Parameters

Item	Value or Min. and Max for clocks	Item	Value or Min. and Max for clocks
Parallel clock (imaging area)	-6.0 V and +4.0 V	Reset drain	-13.6V
Serial clock	-2.0 V and +6.0 V	Reset clock	-6.0 V and 0.0 V
Transfer gate	0 (not clocked)	Backside bias	+25 V
Summing well clock	-5.0 V and +5.0 V	Substrate (frontside contact)	floating
Output gate	+2.0 V	Load resistor	20 K Ω
Output drain	-20 V	Temperature	~ -120 C

Quantum efficiency was measured through a series of narrow-band interference filters, using a calibrated UDT Sensors, Inc. Model PIN UV 100 silicon photodiode as a reference. Full well was measured by determining the signal level at which the device response becomes non-linear. Read noise was found by measuring the pixel-to-pixel variations in a short dark frame. Done in this way, the noise includes any component that might arise from spurious charge generated during the serial register clocking. Ideally no spurious charge would be generated. Initially we did observe some spurious charge, but this was eliminated by adding small capacitors to the serial clock lines to slow the rise- and fall-times. Dark current was measured by doing repeated 1000-second integrations with no illumination. The CCD was maintained at about -120C. The value given in Table 2 was obtained after maintaining the CCD in complete darkness for 24 hours. Charge transfer efficiency (CTE) is difficult to measure accurately in this device, because the device is so small. We estimate the CTE is at least >0.99992 per pixel (<1.6% loss over 200 pixel transfers), but this is rather uncertain and we must await the fabrication of larger devices to obtain a more precise answer. Of special concern for a thick high-resistivity CCD is the effects of charge diffusion. This is discussed in the next section. Our other results are summarized in Table 2 and Figure 2.

TABLE 2. Measured Characteristics at -120 C

Parameter	Value
Charge Transfer Efficiency	>0.99995
Read noise	4-6 e^-
Dark Current	.014e^-/sec
Full Well	300 Ke^-

Standard thinned CCDs are usually about 25 μm thick, and beyond about 800 nm wavelength the absorption length in silicon becomes long enough that the thin silicon membrane begins to act like a cavity, and interference fringes appear. In the present CCDs, which are twelve times thicker, no significant fringing has been observed out to 1000 nm. Figure 2 shows the measured quantum efficiency for a frontside-illuminated CCD (solid line with triangles) and a backside-illuminated CCD (solid line with squares). For comparison, typical quantum efficiencies for low-resistivity commercial CCDs are shown as dotted

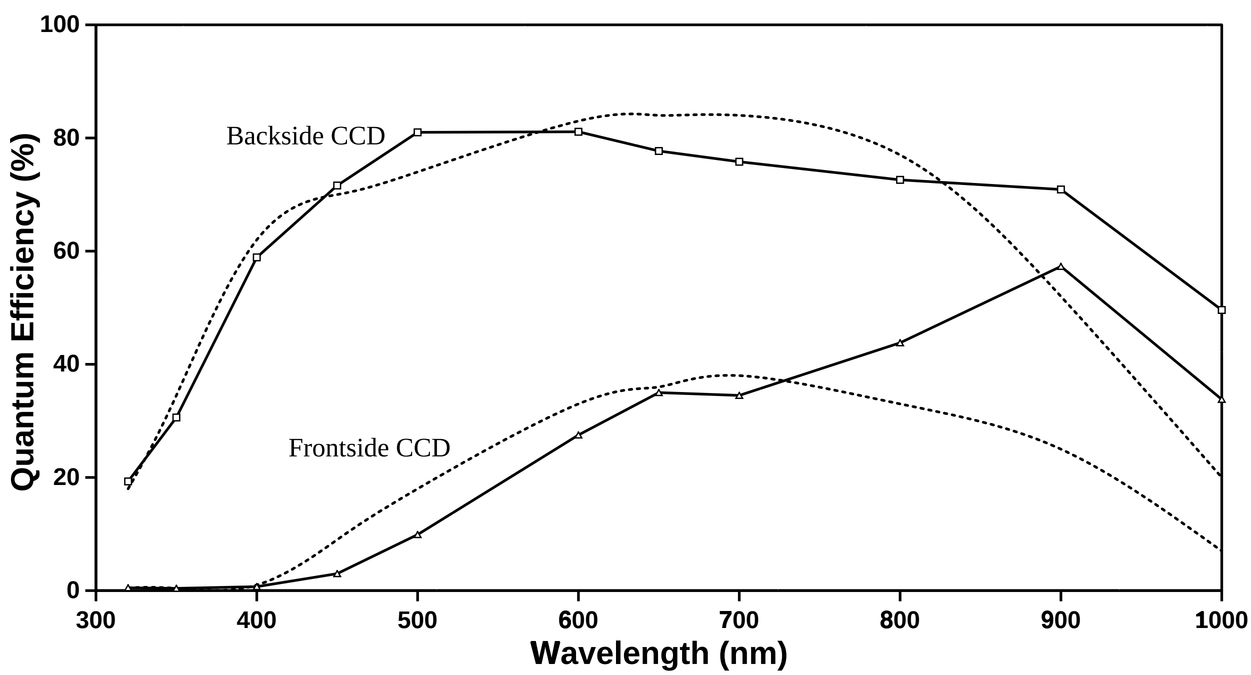

FIGURE 2. Quantum efficiency measurements for both frontside and backside CCDs. Solid lines with symbols are measured values and dotted lines illustrate typical low-resistivity commercial CCD quantum efficiency.

lines. Note the superior red performance beyond 800 nm wavelength, where the extra thickness of the high-resistivity CCD makes it possible to detect more of the incident photons. Good blue response was also obtained with the backside-illuminated device, even though we used no UV-enhancing backside surface treatments as are required in standard p-type silicon CCDs.

3.3 Charge diffusion

Because photo-generated carriers produced near the back of our device must drift 300 μm to the front, diffusion and spreading of the charge is non-negligible.To minimize lateral diffusion we fully deplete the substrate with a backside bias voltage to eliminate any field free regions. Also, by maintaining as high a drift field as possible with the backside bias voltage we keep the transit time across our 300 μm thick device short which also minimizes diffusion, although as shown in Figure 3 the dependence of charge spreading on backside bias voltage is fairly weak once the substrate is fully depleted. To investigate the dependence of charge diffusion on bias voltage we produced a mask with a series of small pinholes. We used 2, 4, and 8 μm pinholes, but it turns out that the size of the pinhole has little effect on the measured spot size. We laid the mask directly on the back surface of the CCD and illuminated the mask with 400 nm light from a small light source. We then varied the backside bias voltage and obtained images of the illuminated pinholes. The RMS spreads in x and y for each spot were computed and the average is plotted versus voltage in Figure 3. We typically operate our backside CCD at 25 volts and at this voltage lateral diffusion is inconsequential in many astronomical applications.

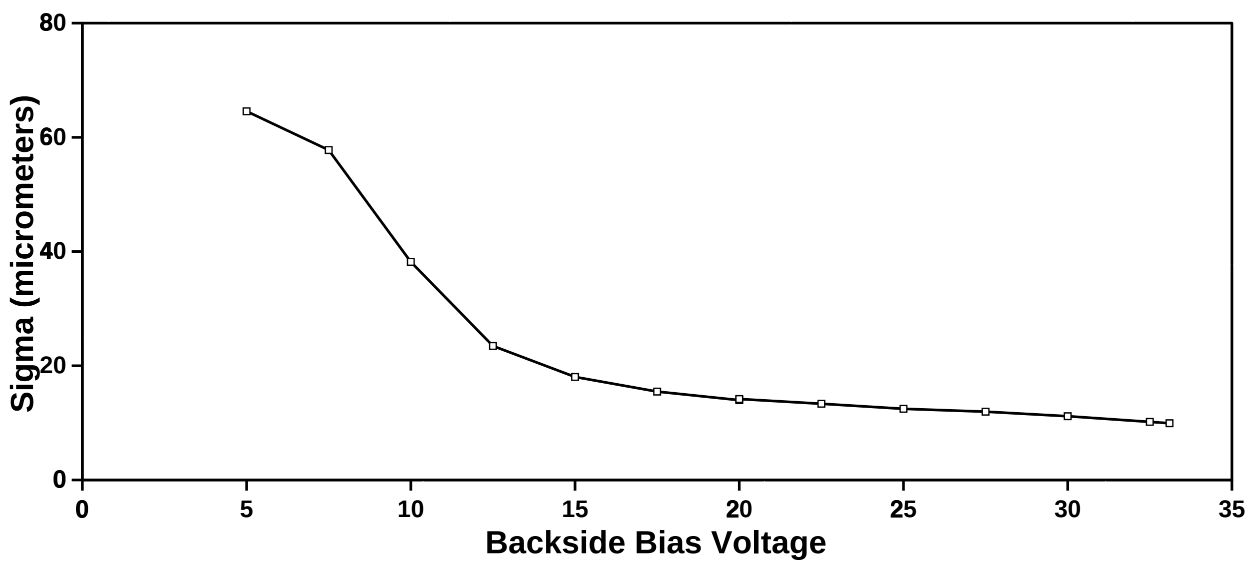

FIGURE 3. Measured charge diffusion versus applied backside bias voltage.

3.4 Cosmic rays

Astronomical exposures can often by very long (up to an hour), and cosmic rays passing through the CCD detector during an exposure can introduce artifacts into the image which must be removed later. Because our CCD is so thick a cosmic ray passing through the device can generate a considerable amount of charge along its path. In addition, self repulsion of this charge will produce enhanced lateral diffusion. As a result, charge deposited near the front of the device will have little opportunity to spread and will be confined to one or two pixels while charge deposited near the back of the device can be spread out over a region 5 to 10 pixels in diameter. This is a significantly different pattern than is observed in typical thinned CCDs. If the cosmic ray enters nearly perpendicular to the CCD surface the event may appear with a sharp core and a diffuse halo. If the cosmic ray enters at a sufficiently large angle (Figure 4) it may appear as a streak with a sharp end and a diffuse tail. Methods for recognizing and removing cosmic ray events from astronomical images will be one of the new challenges for these CCDs.

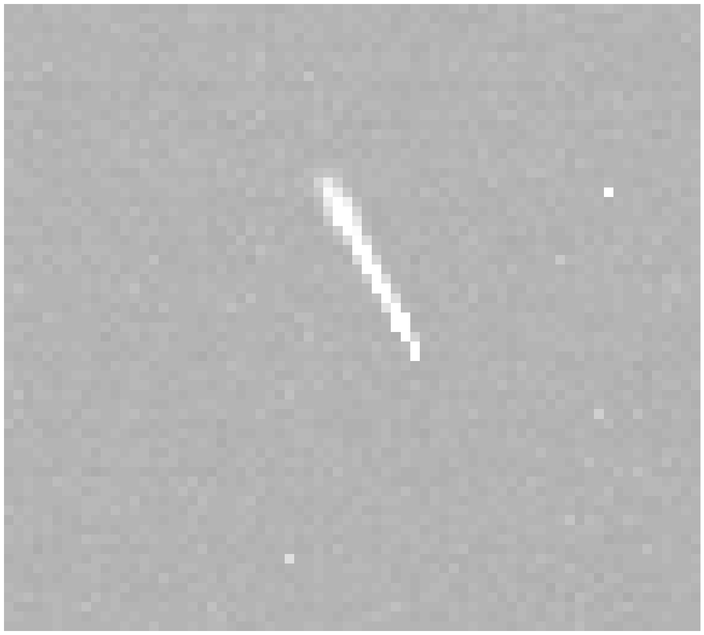

FIGURE 4. An enlargement of a single particle track, possibly a cosmic ray, showing the effect of charge spreading.

4. OBSERVATORY TESTING

To help illustrate the power of our CCD we took our back-illuminated device to the 1-m Nickel telescope at the UCO/Lick Mt. Hamilton observing station on December 4, 1996. We observed the region of the Orion Nebula just southwest of θ Ori, the Trapezium. Figure 5 shows two images taken in the same region. The left image is taken through a Harris R filter, which is a wide-band filter centered roughly at 700 nm wavelength. The right image is taken through a 70 nm bandwidth filter centered at 1000 nm wavelength. Exposure times were 100 seconds for the R band image and 200 seconds for the 1000 nm image.

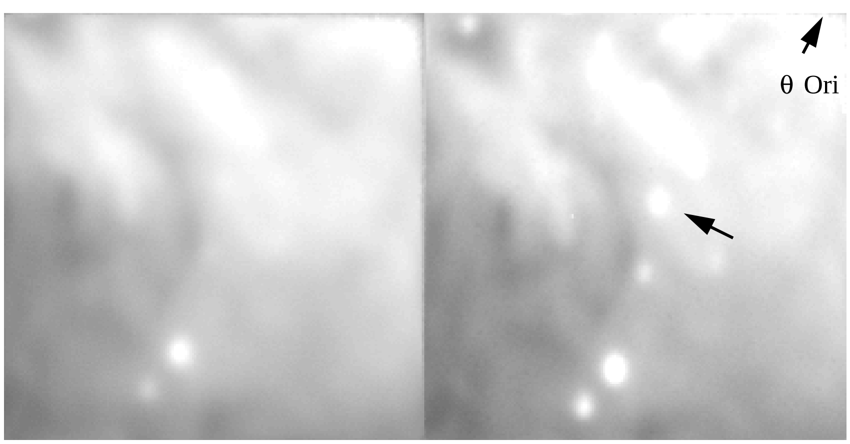

FIGURE 5. Two images of the nebular region southwest of θ Ori. The left image is taken at a wavelength of about 700 nm and the right image is taken at a wavelength of about 1000 nm The arrow indicates a star obscured by dust and gas in the shorter wavelength image.

Note the emergence of star images from the obscuring dust and gas at the longer wavelength (the arrow points out one dramatic example). The 1000 nm image would have been difficult to obtain with a typical low resistivity CCD because of the much lower quantum efficiency and the interference fringes which appear at these wavelengths.

5.CONCLUSIONS

We have characterized a fully depleted high resistivity CCD and we have demonstrated the usefulness of the device at the telescope. We have shown that conventional fabrication techniques can produce an unthinned CCD with excellent response to wavelengths from 350nm to 1000nm and which exhibits no interference fringing out to at least 1000nm. Because the need for thinning is eliminated, fabrication complexity is reduced compared to a thinned CCDs. Future work includes investigation of methods to reduce dark current, tests of better anti-reflection coatings, and the fabrication of much larger devices.

ACKNOWLEDGEMENTS

The work was supported in part by the U.S. Department of Energy under contract No. DE-AC03-76SF00098 and by the National Science Foundation under grant AST 92-26458.

REFERENCES

1. S. Holland, G. Goldhaber, D. E. Groom, W. W. Moses, C. R. Pennypacker, S. Perlmutter, N. W. Wang, R. J. Stover, and M. Wei, “A 200 x 200 CCD Image Sensor Fabricated on High Resistivity Silicon”, *IEDM Technical Digest*, pp. 911-914, 1996.

2. S. Holland, “Fabrication of detectors and transistors on high-resistivity silicon,” *Nuclear Instrum. Methods*, **A275,** 537, 1989.

3. L. B. Robinson, R. J. Stover, J. Osborne, J. S. Miller, S. S. Vogt, and S. L. Allen, “Lick Observatory charge-coupled-device data acquisition system,” *Optical Engineering*, **26**, 795, 1987.